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A comparative study on the environmental impact of greenhouses: A probabilistic approach

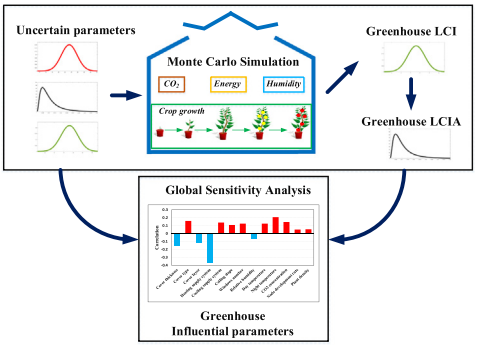
Farzin Golzar [a], Niko Heeren [b,*], Stefanie Hellweg [c], Ramin Roshandel [a]

[a] Department of Energy Engineering, Sharif University of Technology, Tehran, Iran
[b] School of Forestry & Environment, Center for Industrial Ecology, Yale University, USA
[c] Institute of Environmental Engineering, Chair of Ecological System Design, ETH Zurich, Zurich, Switzerland

HIGHLIGHTS

- Drivers for greenhouse environmental impact are indentified by an integrated energy-crop model.
- The most influential parameters are related to crop growth and energy system.
- 85% of climate change impacts in cold climates is due to heating and electricity processes.
- 65% of climate change impacts in hot climates is due to cooling and electricity processes.
- Water scarcity impacts vary greatly for the different greenhouse locations.

GRAPHICAL ABSTRACT



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ABSTRACT

The aim of this study is to investigate the most important drivers of environmental impacts and identify the influence of parameters on the uncertainty of the environmental impacts in various climate zones and future climate scenarios. We couple a combined greenhouse energy demand-yield simulation tool with a life cycle assessment to identify the drivers for greenhouse energy, water and CO_2 demand as well as yield production. Environmental impacts are evaluated using the methods of IPPC for assessing climate change and available water remaining (AWARE) for water scarcity impacts. Furthermore, we compare the results for all five main climate world regions. With a global sensitivity analysis, we identify the parameters with the highest influence on life-cycle impact for each region. Crop growth features (e.g. node development rate and plant density), energy systems (e.g. heating and cooling supply systems), cover materials and inside temperature are the most influential input parameters for climate change impacts, but the ranking between these parameters depends on the location and climatic conditions of the greenhouse. In cold climates and higher latitudes, heating and electricity (mostly for lighting) processes are on average responsible for 85 to 90% of total climate change impacts. In hot climates, active cooling, in addition to natural ventilation, as well as electricity processes rank the highest (in the range of 60 to 75%) and in moderate climates, heating and cooling systems account for 60 to 70% of climate change impacts. Also for the AWARE results, crop growth related parameters are most influential. Among different processes in greenhouse, irrigation is responsible for 90% of water impacts in all regions, but the absolute magnitude of impact varies greatly among the different greenhouse locations.

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* Corresponding author.
E-mail address: niko.heeren@yale.edu (N. Heeren).

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1. Introduction

Remarkable population growth around the world with a decrease in rural labor force has attracted the attention of researchers and policy makers to enhance global food security (Nikos and Jelle, 2012). Food production in greenhouses has been realized as a promoted sustainable production which leads to more yield at the same area of land (Baudoin et al., 2017; Ercilla-Montserrat et al., 2017). However, providing an appropriate condition for crop growth in greenhouse requires energy (particularly in cold and hot climates) and material consumption and consequently environmental impacts (Chen et al., 2016; Maguire et al., 2018; Paladino et al., 2018; Pérez Neira et al., 2018). Therefore, a reliable framework is required to select more sustainable energy systems, structures and management methods among a wide variety of options.

Life cycle assessment (LCA) can be used to evaluate the potential environmental impacts associated with greenhouses (Bartzas et al., 2015; Russo and Scarascia, 2005). A number of studies used LCA as a tool for comparing the environmental burdens of open field tomato production versus protected cultivation in greenhouses (Dias et al., 2017; Martínez-Blanco et al., 2011; Muñoz et al., 2008). LCA has also been used for technology comparisons, including a comparison of various greenhouse typologies and structures (Boulard et al., 2011; Cellura et al., 2012; Russo and Scarascia, 2005; Torrellas et al., 2012b) and different heating systems in cold climates (Heuts et al., 2012) as well as different lighting technologies (Zhang et al., 2017). Further studies analyzed environmental improvement options in greenhouse systems (Tassielli et al., 2018; Torrellas et al., 2012a) and investigated cleaner greenhouse production alternatives (Torrellas et al., 2012a). In addition, Medina et al. (2006), Bojacá et al. (2014) and Khoshnevisan et al. (2014) assessed the environmental impacts of greenhouse crop production in one specific region while Bartzas et al. (2015) and Torrellas et al. (2012b) used LCA for comparing greenhouse environmental impacts in different regions. In recent years, LCA of greenhouses have increasingly been regionalized. For instance, Anton et al. (Antón et al., 2014) improved the greenhouse agricultural LCA studies through spatial differentiation and new impact categories. The aforementioned studies illustrate the ability of LCA to be used as a tool to evaluate and compare different possible alternatives for improving the environmental performance of greenhouses in various climates. However, all of the previous publications focus on single aspects that influence the environmental performance of greenhouses. So far, there exist no studies that comprehensively investigated all three of the following: i. parameters related to location, design, operation, etc. of the greenhouse, ii. the most influential processes (heating and cooling systems, electricity, CO_2 injection, irrigation, structure etc., and iii. the interaction between different combinations of input parameters and the trade-offs for physical processes.

The purpose of this paper is to provide a comprehensive sensitivity analysis to investigate the significance of key processes and parameters affecting the environmental impact of greenhouses in different regions. The results of this study are useful for policy makers and farmers who plan to expand greenhouse cultivation. The study helps them set priorities for agricultural decision making in greenhouse design, operation and siting in an environmentally friendly way.

2. Methodology

To investigate the parameter influence on environmental impact of greenhouse, we propose the following general framework, inspired by the method used in Heeren et al. (2015). It consists of four key steps, as illustrated in Fig. 1: 1) Monte Carlo sampling of random parameters, 2) integrated energy and crop yield calculation using the integrated model by Golzar et al. (2018), 3) life cycle impact assessment (LCIA), and 4) global sensitivity analysis by means of Kendall τ parameter correlation.

2.1. Monte Carlo simulation (step I)

In Monte Carlo simulations (MCS), uncertain input parameters are sampled randomly following pre-defined probability density functions. In the current paper, probability distributions were based on data in literature where possible (Table 1). If no data was available from the literature, we had to make assumptions. For instance, we assumed discrete uniform distribution for the choice of the most common types of cover materials, heating and cooling systems. The probability function densities of uncertain input parameters are summarized in Table 1. The parameters are categorized by greenhouse design (e.g., cover material thickness, ceiling slope and number of windows), operation (e.g., day and night inside temperature set points, relative humidity, CO_2 concentration) and crop growth (e.g., node development rate and plant density). All analyses assumed a 1-hectare size greenhouse.

The generated samples were used as the inputs of greenhouse integrated energy-crop growth model (Golzar et al., 2018). From the distributions in Table 1, random samples were generated. As detailed in Supporting information (SI) 2, we determined that 6000 iterations lead to model convergence for all result parameters (i.e. convergence threshold drops below 1%).

2.2. Integrated energy–yield model (step II)

Golzar et al. (2018) developed a physical model of greenhouse energy demand according to dynamic energy and mass balance while yield production was based on physiological crop model. The integrated model investigates the interrelations between greenhouse energy demand and crop growth due to evapotranspiration, CO_2 assimilation, lighting demand etc. In the present work, it is assumed that the flue gas of heating system compensates the deficit of CO_2 concentration and in case of no fulfilling; CO_2 injection from liquid CO_2 tank is used. Artificial lighting controlled by the amount of daily light needed by plant ($25\ mol \cdot m^{-2} \cdot day^{-1}$ for tomato (Mattson, 2015)), daily solar radiation of greenhouse location and light transmittance of cover materials (Mattson, 2015; Zhang et al., 2017). In this work, two kinds of time steps (hourly and daily) are considered: i. the energy model has an hourly resolution and ii. the crop yield model has a daily resolution (Golzar et al., 2018).

To investigate the influence of diverse climates on technical and environmental impact of greenhouse tomato production, we selected representative climate stations for the main world climate regions, according to the Köppen climate classification (Arnfield, 2017). Bangkok represents the tropical climate (A), Cairo Dry Hot (Bh), Tehran Dry cold (Bk), Izmir Temperate Hot Summer (Ca), Wageningen Temperate Warm Summer (Cb), and Lulea the Continental Cold Summer climate (Dc), respectively (Table 2). Furthermore, future changes in climate, based on 2030 IPCC B1 (Projections of Future Changes in Climate, 2007), were taken into account to assess future changes in greenhouse environmental impact. Table 2 provides typical climate indicators for the selected greenhouse locations: Heating degree days (HDD) is an indicator for the energy demand required to maintain a given indoor temperature, cooling degree days (CDD) are analogue for cooling energy demand. Furthermore, the table provides annual average temperature (AAT) and global horizontal irradiation (GHI). The comparison of HDD in Table 2 shows that Lulea and Wageningen are more rigid climates where require more heating energy. Comparing CDD values shows that Bangkok and Cairo will require more cooling energy supply than the other stations. Future climate scenarios (2030 IPCC B1 (Projections of Future Changes in Climate, 2007)) show that climate conditions change differently for different regions. For example, in Lulea, Wageningen and Izmir, AAT increases, while it remains constant for Tehran and Cairo and decreases for Bangkok.

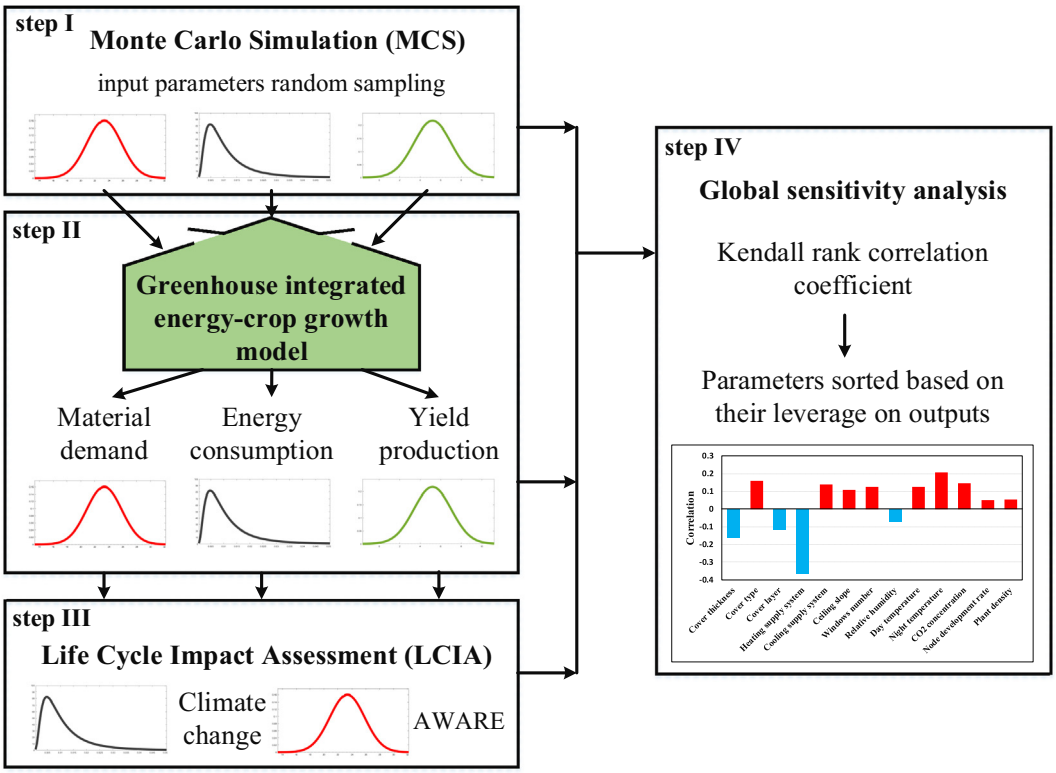

Fig. 1. Schematic representation of methodology.

2.3. Life cycle assessment (step III)

The results of integrated energy-yield model are the input life cycle inventory (LCI) for the life cycle assessment step. We used ecoinvent 3.4 (Wernet et al., 2016) and Brightway2 (Mutel, 2014) to calculate climate change impacts with IPPC Global Warming Potentials of 100 year time horizon (kg CO_2-eq (Stocker et al., 2013)) and Available WAter REmaining (m^3/m^3 (Boulay et al., 2018)). The AWARE method quantifies the impact of water scarcity to both humans and ecosystems, based on the assumption that the likelihood of water deprival increases with smaller water availability (Boulay et al., 2018; Iooss and Lemaître, 2015). The AWARE characterization factors presented in Table S.6 are based on watershed level values. In the present work, agricultural AWARE characterization factors are coupled with the integrated greenhouse energy-crop growth model to calculate AWARE impact scores of different processes. SI 1 (Tables S.2 to S.4) documents the LCI data that were not available from ecoinvent and created for this study. The functional unit is 1 kg of tomato yield produced in 1-hectare commercial greenhouses. System boundaries are cradle-to-grave for construction materials and cradle-to-gate for tomatoes. That means all impacts related to tomato production, transport, energy demand, and renewal of cover materials were taken into account. Lifetime amount of greenhouse and cover materials depends on a wide variety of factors such as climate condition and greenhouse management. However, service life of the greenhouse in this work was assumed to be 20 years (Schatzer et al., 1994) while glass, fiberglass, polycarbonate and polyethylene cover materials were assumed to be replaced every 20, 13, 8 and 3 years, respectively. These assumptions are based on ASABE standards for commercial greenhouse design and layout (American Society of Agricultural and Biological Engineers, 2004). Therefore, material impacts during whole greenhouse lifetime (20 years) was calculated and divided by 20 to analyze annual yield production climate impacts.

2.4. Global sensitivity analysis (step IV)

Global sensitivity analysis (Iooss and Lemaître, 2015) takes into account the results of MCS to distinguish the rank order correlation between uncertain input parameters and output vectors (e.g. water and CO_2 demand, energy consumption, yield production and environmental impacts). Due to non-normal distribution of some parameters, the Kendall τ correlation was selected as coefficient (Heeren et al., 2015; Kendall, 1938). Greater coefficients show a stronger relationship between input parameter and output. Moreover, positive numbers show that increasing of a parameter will lead to an increase in the output. In contrast, negative coefficients have reverse effect. Results with low statistical significance (p value lower than 0.01) were omitted because of their low reliability.

3. Results and discussion

In this section we will first document the overall LCIs as calculated by the integrated crop-yield model (see step II in Fig. 1) and LCIAs (step III in Fig. 1). Next, we present (step IV) the correlation results between the input parameters (step I) and LCIs and LCIA results, respectively.

3.1. Life cycle inventories (LCIs)

In the present work, the technical performance of the greenhouse in various climates is investigated by six outputs including greenhouse heating demand, cooling demand, electricity demand, CO_2 demand for the aim of CO_2 enrichment, water demand and yield production. The boxplots of aforementioned outputs for different climates are depicted in Fig. 2 comparing energy, CO_2 and water demand for producing 1 kg tomato.

The general comparison of Fig. 2 shows that energy demands (cooling, heating and electricity) are more sensitive to outdoor climates

Table 1
Analysis of sensitivity inputs (parameters are varied individually and independently) for the greenhouse.[a]

	Parameter [unit]	Distribution	Scenario range	Description, source
Greenhouse design and material	Cover thickness [m]	Lognormal	$\mu = -5.50$; mdn. = 0.006 $\sigma = 0.32$; 0.95% CI (0.001, 0.015)	Independent parameter that affects thermal heat loss from greenhouse, solar radiation into greenhouse and cover material lifetime. Distribution is found based on values from producers and experts of glass as greenhouse cover material ("*Greenhouse covering materials comparison – glass, polycarbonate, polyethylene, fiberglass, acrylic and vinyl*", 2017; "*Greenhouses: how to choose & where to buy*", n.d.; Guinness, 2009).
	Cover type	Discrete uniform	Glass, fiberglass, poly carbonate, poly ethylene	The most conventional greenhouse cover materials ("*greenhouse covering materials comparison – glass, polycarbonate, polyethylene, fiberglass, acrylic and vinyl*", 2017). We assumed the material lifetimes were assumed to be: 20, 13, 8 and 3.
	Heating supply system	Discrete uniform	Hard coal furnace, fuel oil boiler, natural gas boiler, CHP, solar and gas boiler hybrid, wood chips furnace, water heat pump, Air heat pump[b]	Systems and data (including conversion efficiency) based on Ecoinvent (Weidema et al., 2013)
	Cooling supply system	Discrete uniform	Absorption cooler, evaporation cooler	Systems and data based on Finocchiaro et al. (2016), Rey Martínez et al. (2011), Weidema et al. (2013).
	Ceiling slope [°]	Lognormal	$\mu = 2.87$; mdn. = 30 $\sigma = 0.44$; 0.95% CI (10, 70)	Roof slope as an independent parameter that affects natural ventilation and greenhouse solar radiation. Based on literature values (Çakır and Şahin, 2015).
	Windows number [window m^{-2}]	Lognormal	$\mu = -2.64$; mdn. = 0.3 $\sigma = 0.21$; 0.95% CI (0.1, 0.9)	A construction design parameter that affects natural ventilation. Values for distribution are determined from literature values (De Zwart, 1996).
Greenhouse operation	Relative humidity [%]	Normal	$\mu = 70$; mdn. = 70 $\sigma = 3.00$; 0.95% CI (60, 90)	A parameter that affects the water content of greenhouse inside air. Based on literature values (Ahemd et al., 2016; Van Beveren et al., 2015).
	Day temperature [°C]	Normal	$\mu = 25$; mdn. = 25 $\sigma = 2.64$; 0.95% CI (22, 32)	A parameter that affects the lower and upper bound of the inside temperature during the day. Based on literature values (Heuvelink, 1989; Sato et al., 2000; Van Beveren et al., 2015).
	Night temperature [°C]	Normal	$\mu = 16.61$; mdn. = 16.61 $\sigma = 4.23$; 0.95% CI (14, 20)	A parameter that affects the lower and upper bound of the inside temperature during the night. Based on literature values (Heuvelink, 1989; Sato et al., 2000; Van Beveren et al., 2015).
	CO_2 concentration [ppm]	Normal	$\mu = 625.83$; mdn. = 625.83 $\sigma = 249.63$; 0.95% CI (350, 850)	A parameter that affects the CO_2 concentration of greenhouse inside air, available for plant photosynthesis by plants. Based on literature values (E., 2004; Mortensen, 1987; Nederhoff and Vegter, 1993; Sato et al., 2000; Van Beveren et al., 2015).
Crop growth	Leaves thermal resistance [s m^{-1}]	Uniform	a = 150; b = 250	A physiological parameter that affects crop transpiration. Values for distribution are determined from Van Beveren et al. (2015).
	Node development rate [node h^{-1}]	Uniform	a = 0.01; b = 0.04	A physiological parameter that affects node development rate and LAI production. Values for distribution are determined from Jones et al. (1999) and Ramirez et al. (2004).
	Plant density [plant m^{-2}]	Normal	$\mu = 3.16$; mdn. = 3.16 $\sigma = 0.55$; 0.95% CI (1, 6)	An agricultural management parameter that affect transpiration and yield. Values for distribution are determined from Jones et al. (1999) and Ramirez et al. (2004).
Exogenous	Climates	Discrete choice	Bangkok, Cairo, Tehran, Izmir, Wageningen, Lulea	Climate data (solar radiation, temperature, wind speed, relative humidity). Data: Meteonorm (Meehl et al., 2007). More climates description presented in Section 2.3.

[a] μ and σ are the location and scale parameters. Mdn is the median and 95% CI the 2.5th and 97.5th percentile (enclosing the 95% confidence interval).
[b] Heating supply systems are defined from a high CO_2 emission to low CO_2 emission sequence.

than water and CO_2 demand and yield production (compare Fig. 2.a, b, c with d, e, f). The reason is that energy demand is a function of the difference between greenhouse indoor conditions (temperature, relative humidity and lighting) and outdoor climate. In contrast, since all greenhouse inside microclimates are assumed to be the same in all locations, the difference in CO_2 demand, water demand and yield production is less than the difference in energy demands. However, also CO_2 and water demand as well as yield production are indirectly function of outdoor climes. For instance, water demand is a function of evapotranspiration and evapotranspiration is a function of solar radiation. As a result, water demand is influenced by outdoor climates, although this influence is rather small (Fig. 2.e). However, yield production, CO_2 and water demand are a function of indoor microclimate. Therefore, greenhouse management directly influences them. Please refer to Table S.13 for more details on the drivers for these outputs.

Since Wageningen and Lulea have a comparatively low outside temperature and solar irradiation (see Fig. S.2.b in SI), they have the highest heating demand of all locations considered. On the other hand, in hot climates such as Bangkok and Cairo, cooling demand is the crucial output. Although heating demand in Bangkok is ignorable, heating demand in Cairo is considerable due to cold nights. Comparison of Tehran and Izmir as two moderate climates demonstrates that Izmir demands both lower heating and cooling demand than Tehran.

The most substantial part of electricity demand in greenhouses is related to artificial lighting. As a result, regions with higher latitudes (51.96° for Wageningen and 65.58° for Lulea) need dramatically more electricity for artificial lighting than rest of regions. However, the artificial lighting demand is not only a function of latitude, but also it depends on environmental parameters preventing solar radiation such as number of cloudy days and relative humidity. For instance, even though the latitude of Bangkok is lower than Cairo and Tehran, Bangkok needs more artificial lighting, owning to higher outdoor relative humidity (see Fig. S.2.c in SI).

Net CO_2 demand, presented in Fig. 2.d, is the amount of CO_2 needed for crop growth minus the amount of CO_2 produced as flue gas by the heating system. As a result, cold places demanding more heating and producing more flue gas, demand less CO_2 from liquid CO_2 tank.

Although greenhouse water demand is not highly influenced by various climates, it is mostly governed by crop evapotranspiration which is a function of solar radiation. Therefore, climates with lower solar radiation need relatively less water. For instance, Wageningen with the lowest solar radiation needs approximately 55% on average less water than Cairo with the highest irradiation. In addition, ventilation removes humidity from the greenhouse and hence ventilation rate influences water demand.

Fig. 2.f presents yield production. Because of its dependency on greenhouse microclimate, the produced yields in all climates are similar.

Table 2
Selected climates based on Köppen classification (Arnfield, 2017).

Köppen climate (city, country)	Criteria	Latitude (°N)	HDD[a]/year (degree day)		CDD[b]/year (degree day)		AAT[c] (°C)		GHI[d] (kWh/m^2·year)	
			2010	2030	2010	2030	2010	2030	2010	2030
Tropical, A (Bangkok, Thailand)	Temperature of coolest month 18 °C or higher	13.75	0	0	4018	3923	28.9	28.6	2200	2145
Dry, Bh (Cairo, Egypt)	Average annual temperature equal to or greater than 18 °C	30.04	260	256	1957	1971	22.5	22.5	2527	2714
Dry, Bk (Tehran, Iran)	Average annual temperature less than 18°C	35.68	1484	1598	1670	1705	18.4	18.4	2620	2604
Temperate, Ca (Izmir, Turkey)	Temperature of warmest month 22 °C or above (hot summer)	38.42	1003	1369	1338	1151	17.3	18.8	2542	2163
Temperate, Cb (Wageningen, The Netherlands)	Temperature of each of four warmest months 10 °C or above but warmest month less than 22 °C (warm summer)	51.96	2775	2820	88	92	10.5	10.6	1418	1398
Continental, Dc (Lulea, Sweden)	Temperature of one to three months 10 °C or above but warmest month less than 22 °C (cold summer)	65.58	5287	5355	18	21	3.4	3.7	1577	1496

[a] Annual heating degree days (18 °C base temperature).
[b] Annual cooling degree days (18 °C base temperature).
[c] Annual average temperature.
[d] Global horizontal irradiation.

3.2. Life cycle impact assessment (LCIA)

3.2.1. Climate change impacts

Fig. 3 demonstrates the detailed climate change impacts of greenhouse and compares various climates. The overview of Fig. 3 shows that heating system, cooling system, electricity supply and structure have more role in climate change impacts than CO_2 injection, irrigation and consumables for crop growth. However, in different climates, the order of these processes is different. For instance, in cold climates like Wageningen and Lulea, the heating system has the most impactful

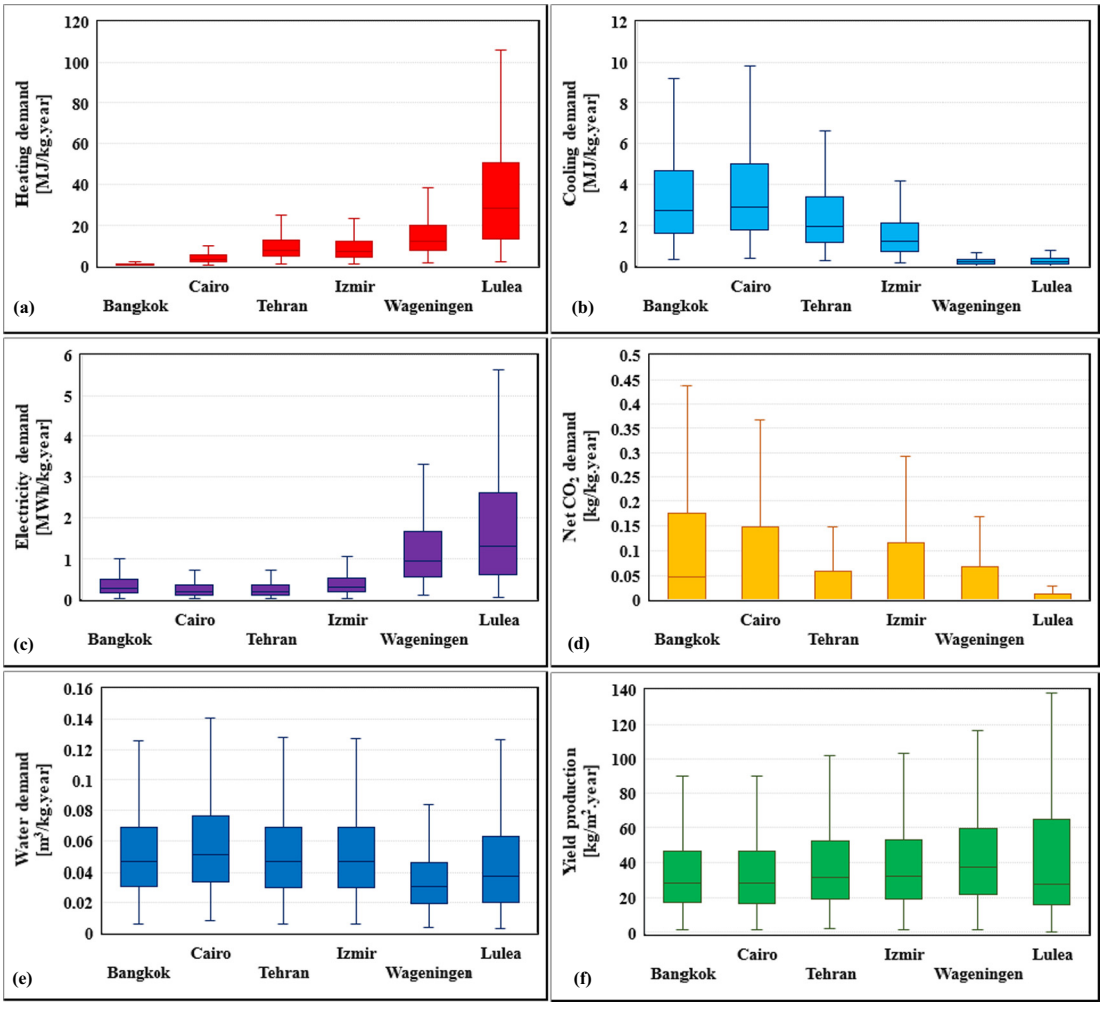

Fig. 2. Comparison of greenhouse annual energy, CO_2 and water demand as well as yield production in different climates. a: Greenhouse heating demand. b: Greenhouse cooling demand. c: Greenhouse electricity demand. d: Greenhouse net CO_2 demand for CO_2 enrichment. e: Greenhouse water demand. f: Greenhouse yield production.

role while in hot climates such as Bangkok and Cairo cooling system has the biggest impact on climate change.

Electricity supply is the second most impactful process in Wageningen where has high demand of electricity. Even though Lulea has higher electricity demand than Wageningen, the electricity process has lower environmental impact in Lulea than Wageningen. The reason is that the share of electricity generation in Lulea (Sweden) is 47% hydro power, 34% nuclear power and 10% wind power and only 9% comes from combustion based production (*Energy in Sweden 2017*, 2018). As a result, due to low specific impact per kWh the climate change impact score of electricity is lowest in Lulea although it has the highest electricity demand. In contrast, 81% of produced electricity in Netherlands comes from fossil fuels (Ras, 2017). Therefore, high electricity demand and high specific impact per kWh of electricity result in the fact that electricity supply in a greenhouse in Netherlands has the highest impact than other climates. We also combined all climates and compared influential parameters in Table S.13 in SI.7, which confirms that the CO_2 of electricity mixed is significantly influential on climate change impacts.

The last column of Fig. 3 compares the total climate change impacts of a commercial greenhouse in different climates. The general trend shows that a greenhouse in Lulea has the highest climate change impacts. Although the climate change impacts caused by cooling system and electricity supply in Lulea are the minimum values among other climates, the high climate change impacts of heating system causes that Lulea would have the highest climate change impacts. Per kg of tomato produced, the following ranking in terms of environmental impacts was obtained (in increasing order): Bangkok, Cairo, Tehran, Izmir, Wageningen and Lulea. This order shows the dominant role of heating system on climate change impacts.

More results about the share of impactful processes on climate change in each location are presented in SI 4. It shows that 85 to 90% of climate change impacts in cold climates and higher latitudes are due to heating and electricity (mostly for lighting) processes. In hot climates, cooling and electricity processes are responsible for 60 to 75% of climate change impacts while in moderate climates heating and cooling supply systems account for 60 to 70% climate change impacts.

3.2.2. Water use impact

Fig. 4 depicts the detailed AWARE impact score of greenhouse at various locations. Irrigation is the most dominant process affecting water use in all locations. Fig. S.5 demonstrates that 83 to 90% of water use in all climates is due to irrigation processes. In hot climates, cooling systems are responsible for 5 to 8% of water use while in cold climates, heating and electricity systems are responsible for 6 to 10% of water use. The last column of Fig. 4 compares the total water use impacts of a commercial greenhouse in different climates. The general trend shows that greenhouses in Cairo, Tehran and Izmir have high water use impacts, while impacts are much lower for the other locations. The reason is that the AWARE characterization factors are higher for Cairo, Tehran and Izmir than for Bangkok, Wageningen and Lulea, reflecting the large variability in regional conditions of water scarcity. Per kg of tomato produced, the following ranking in terms of water use impacts was obtained (in increasing order): Wageningen, Lulea, Bangkok, Izmir, Tehran, and Cairo. More results about water use impact are presented in SI 5.

3.3. Sensitivity analysis

3.3.1. Contribution to variance

Correlation between input parameters and climate change impacts are summarized in Table 3. Moreover, five most impactful parameters are sorted in Table 4. The most two important parameters for all climates are node development rate and plant density which are related to crop growth. It shows that for the same amount of material and energy consumption, higher node development rate and plant density produce more yield and accordingly cause less environmental impact for 1 kg tomato produced. Although farmers cannot directly control node development rate during cultivation, they should pay attention to this parameter when they want to select the appropriate tomato cultivar for their greenhouse. The cultivars with higher node development rate perform best, but they are more sensitive to their environment and management practices (Jones et al., 1999) and are therefore not an option for low-tech greenhouses which cannot provide suitable microclimate conditions. Plant density is another crucial parameter that farmers decide on at the beginning of planting. Yield increases with plant density, but very high plant density can cause trouble in crop respiration. Hence, only greenhouses with suitable heating and cooling distribution system can work with high plant density.

Moreover, correlation coefficients for node development rate and plant density decrease from hot climates to cold climates which shows that in colder climates heating systems and electricity supply decrease the dominant impact of crop growth parameters.

In hot climates (Bangkok and Cairo), apart from crop-related parameters, night temperature and cooling systems have the most influential impact. On the other hand, in moderate and cold climates, apart from crop-related parameters, heating supply systems and other parameters such as day temperature, cover type and thickness affecting heating demand, are influential. In Table 3, an increase in heat supply system means selecting cleaner technologies (see Table 1) and results in less climate change impacts. The cooling supply system is not influential in cold climates like Wageningen and Lulea. However, in hot climates cooling technology matters, i.e. an evaporation cooler causes more environmental impacts than an absorption cooler, because evaporation cooler consumes both electricity and water (as shown in Table S.4) while absorption chiller only consumes electricity. Despite the fact that absorption coolers are more environmentally friendly, evaporation

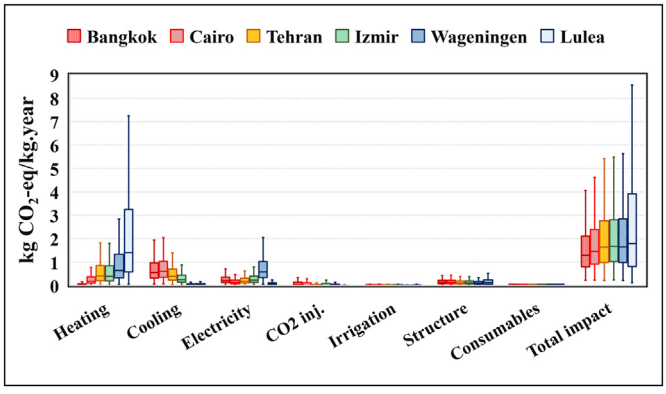

Fig. 3. Comparison of different processes of greenhouse affecting climate change [kg CO_2/kg tomatoes] in different regions. Last column is the sum of all processes.

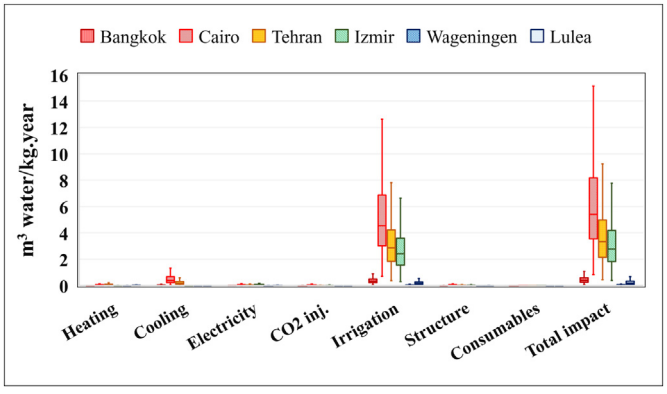

Fig. 4. Comparison of different processes of greenhouse affecting water use [m^3 water/kg tomatoes] in different regions. Last column is the sum of all processes.

Table 3
Kendall τ correlation for each input parameter (row) and yield-specific climate change impacts [kg CO_2/kg tomatoes] (column)[a]. Gray cells show Kendall τ correlation for greenhouse demands and yield production (row) and climate change impacts [kg CO_2/kg tomatoes] (column).

Parameter			climate change impact (LCIA)					
			Bangkok	Cairo	Tehran	Izmir	Wageningen	Lulea
Model input parameters	Design	Cover thickness	-0.04	-0.04	-0.14	-0.08		-0.05
		Cover type	0.06	0.06	0.13	0.08		0.04
		Heating supply system		-0.07	-0.15	-0.16	-0.19	-0.21
		Cooling supply system	0.16	0.15	0.07	0.06		
		Ceiling slope		0.05				
		Windows number	0.05	0.06				
	Operation	Relative humidity						
		Day temperature	-0.11	-0.10	-0.13	-0.10	-0.12	-0.18
		Night temperature	-0.17	-0.13	-0.08	-0.06	-0.07	-0.04
		CO_2 concentration	-0.11	-0.10	-0.13	-0.14	-0.15	-0.11
	Crop	Leaves thermal resistance						
		Node development rate	-0.52	-0.52	-0.48	-0.48	-0.46	-0.35
		Plant density	-0.49	-0.47	-0.44	-0.43	-0.40	-0.31
Model outputs (LCI)		Heating demand	-0.10	-0.10	-0.12	-0.15	-0.17	-0.21
		Cooling demand	0.19	0.15	0.10	0.10	0.07	0.07
		Electricity demand			0.07		0.09	
		CO_2 injection			-0.04		-0.05	-0.07
		Yield production	-0.61	-0.60	-0.54	-0.53	-0.50	-0.31

[a] Positive coefficients (blue bars) present that an increase of the parameter (row) result in an increase in climate change impact (column); vice versa for negative coefficients (red bars). Blank cells have *p*-values less than 0.01. Cover type increase means cover selection from 1. glass, 2. fiberglass, 3. poly carbonate, 4. polyethylene. Heating supply system increase means technology selection from 1. hard coal furnace, 2. fuel oil boiler, 3. natural gas boiler, 4. CHP, 5. solar and gas boiler hybrid, 6. wood chips furnace, 7. water heat pump, 8. air heat pump. Cooling supply system increase means technology selection from 1. absorption cooler, 2. evaporation cooler.

coolers (e.g. fan and pads) are more common in commercial greenhouses due to their cheaper price.

The lower part of Table 3 shows the correlation between the greenhouse model results (i.e. LCI) and climate change impact (LCIA). In all regions, yield production has the strongest correlation with climate change impact although its magnitude decreases from hot climates to cold climates. In the second rank is heating demand for cold places and cooling demand for hot regions. The negative values for heating demand show that by increasing heating demand, climate change impact would be decreased. The reason is that when heating demand increases, both GHG emissions as well as yield production increase, while the relative effect on yield is higher. Since it is the denominator of the chosen result vector (i.e. kg CO_2-eq/kg tomato produced), the impact score decreases. These results confirm that increasing yield production does not necessarily mean a decrease in GHG impact. Therefore, the relative influence of both yield production and climate change impacts must be considered.

As shown in Fig. 4, location is the most influential factor on water use due to different water scarcity in various locations. However, the impactful parameters in each location are specified by Kendall τ correlation (SI 5). Correlation shows that node development rate is the most crucial parameter in each region and tomato cultivar selection is an important decision from water use point of view, too. The second important parameter is plant density in all regions except Lulea where day temperature in the greenhouse is the second crucial parameter. Night temperature, CO_2 concentration and relative humidity are next important parameters in all regions. Besides, crop growth as well as operation parameters are more impactful on AWARE than design parameters.

3.3.2. Climate scenario

Climate change impact based on 2030 climate scenario is compared with the results of 2010 climate and presented in Fig. S.6. It shows that future climate scenario does not have the same effect on climate change impact in all regions. Lulea, Wageningen and Tehran are affected more than the other regions. In Lulea and Wageningen, the solar radiation will decrease particularly in winter. Therefore, heating demand and accordingly climate change impact will increase. In Tehran, the increase of wind speed causes more heat loss and more climate change impact. On the other hand, in Bangkok, Cairo and Izmir, although climate conditions will change, it contributes to no considerable variation in climate change impact. For instance, solar radiation in Izmir will decrease mostly during summer and cause decrease in cooling demand. On the other hand, wind speed will increase which causes to increase heating demand and generally results in no change in climate impact. However, energy demand (heating and cooling demands) are affected remarkably

Table 4
Top 5 most influential input parameters for climate change impacts [kg CO_2/kg tomatoes] as of Table 3, sorted by their influence. The values in brackets denote Kendall τ correlation for each input parameter.

Rank	Bangkok	Cairo	Tehran	Izmir	Wageningen	Lulea
1	Node development rate (−0.52)	Node development rate (−0.52)	Node development rate (−0.48)	Node development rate (−0.48)	Node development rate (−0.46)	Node development rate (−0.35)
2	Plant density (−0.49)	Plant density (−0.47)	Plant density (−0.40)	Plant density (−0.43)	Plant density (−0.40)	Plant density (−0.31)
3	Night temperature (−0.17)	Cooling supply system (0.15)	Heating supply system (−0.15)	Heating supply system (−0.16)	Heating supply system (−0.19)	Heating supply system (−0.21)
4	Cooling supply system (0.16)	Night temperature (−0.13)	Cover thickness (−0.14)	CO_2 concentration (−0.14)	CO_2 concentration (−0.15)	Day temperature (−0.18)
5	Day temperature (−0.11)	CO_2 concentration (−0.10)	Cover type (0.13)	Day temperature (−0.10)	Day temperature (−0.12)	CO_2 concentration (−0.11)

by future climate conditions. Kendall τ correlation rank order analysis for 2030 climate conditions (SI 6) shows that node development rate and plant density remain to be the two most influential parameters in all regions. Parameter ranking order in 2030 shows that operation parameters affecting energy demands like day and night temperatures, CO_2 concentration and relative humidity will be more influential than heating and cooling supply systems. The reason is that energy supply systems determine the type and amount of energy *consumption* and do influence greenhouse energy *demand*. However, in 2030, when greenhouse energy demand plays a more important role, operation parameters also have more effect.

3.4. Comparison with literature

The results of this paper are in good agreement with previous studies as summarized in Table 5. Dias et al. (2017) reported that the climate change impacts of heated greenhouses in different regions are in the range of 1.7 to 5.1 kg CO_2-eq/kg product while the present work reports this value in the range of 1.5 to 2.8 kg CO_2-eq/kg product. For instance, Dias et al. (2017) presented that climate change impacts is 2 kg CO_2-eq/kg product in Netherlands and this work shows that this value for Wageningen is 2.4 kg CO_2-eq/kg product. Almeida et al. (2014) believed that the most important processes for the environmental impact of tomato greenhouse in northern Italy are heating, electricity and CO_2 enrichment. In this work, the most influential processes for a climate like northern Italy (Izmir based on Köppen classification) are heating, cooling and electricity as well as CO_2 enrichment. Torrellas et al. (2012b) investigated that the main environmental burden of tomato greenhouse production in northern European countries is energy consumption for heating and lighting. This result coincides with the result of this work that the most influential process in Lulea (Sweden) is heating. In addition, the lighting demand in Lulea is dramatically high but due to clean electricity production in Sweden, the electricity caused by lighting demand has less impact. Khoshnevisan et al. (2014) showed that the environmental impact of greenhouse production in Iran is dominated by natural gas and electricity where natural gas is used for heating demand and electricity for cooling demand. The analysis of climate change impacts in Tehran in the present work shows that heating and cooling are two most influential processes. In contrast to previous studies that focused on one specific climate region, the proposed model in this paper can be applied to any climate condition. The reason is that the proposed framework is coupled with an integrated energy-crop growth model calculating the energy consumption and yield production of greenhouse related to a given climate. The comparison of results of this paper with the literature shows that the proposed methodology is able to accurately assess the influence of different regional climates, design and operation on the environmental impact of greenhouse crop production.

3.5. Recommendations

Since energy demand, particularly heating demand in cold climates is one of the most important drivers of greenhouse environmental impact, greenhouse holders or planners may want to decrease it by use of thicker cover materials. However, Table S.13 (SI 7) demonstrates that although thicker cover material causes less heating demand, it leads to more lighting demand. As a result, in climates like Lulea which electricity for lighting has low environmental impact, it is recommended to use thick cover materials to decrease heating demand, but this may be different in other locations with other electricity mixes. In addition, in northern countries with lower solar radiation, it is better to cultivate crops with lower lighting demand like cucumber and lettuce than tomato. In hot climates, where cooling demand is the most influential driver, focusing on natural ventilation could decrease the environmental impact of cooling system. However, increasing natural ventilation results in increasing CO_2 and water loss. Therefore, natural ventilation should be controllable. In moderate climates where both heating and cooling demand are influential, a control system is recommended. Since during one day, greenhouse could need both heating and cooling, a control system would easily fulfill the demands by use of natural ventilation or shadings. Besides, short-term thermal storage technologies such as phase change materials (PCMs) could decrease or remove the demand of active heating or cooling (Golzar et al., 2018). However, the environmental impact of additional material should be investigated.

However, if greenhouses would restrict their production to those crops that are most suitable for a given climatic condition, transport could indeed increase. Previous studies have shown that transport impacts are typically small compared to the energy savings that can be achieved by better sourcing from energy-low greenhouse locations (e.g. Stoessel et al., 2012). This finding would however not be correct for airplane transport, but the crops we are discussing in the paper would most likely be transported by truck and ship.

4. Conclusion

In this study, the environmental impacts of greenhouse tomato production in all five main climate world regions are investigated. The method implemented in this work was based on a global sensitivity analysis to realize input parameter leverage on LCIs (energy, CO_2 and water demand as well as yield production) and LCIA (climate change and water use (AWARE)).

With regard to climate change impacts, the dominant processes are dissimilar in different climate zones. Greenhouse tomato production in cold climates has more environmental impacts than in moderate and hot climates. Heating systems are the most dominant process in cold climates. Besides, in cold climates with higher latitudes, lighting demand and accordingly electricity demand is the second influential process. In hot climates, cooling systems and electricity supply are the two most important processes. Since heating supply systems in these climates do not produce enough flue gas containing CO_2 (due to low heating demand), supply from liquid CO_2 tank is needed for CO_2 fertilization in these climates. In moderate climates, both heating and cooling systems are dominant.

From water use (AWARE) point of view, the overall affects primarily driven by local conditions of water scarcity. In all locations, irrigation

Table 5
Comparison of literature results with current work.

Reference	Comparison criteria	Reference value from the literature	Present work value
Dias et al. (2017)	Range of climate change impacts of heated greenhouses	1.7 to 5.1	1.5 to 2.8
Dias et al. (2017)	Climate change impacts of greenhouses in Netherlands	2	2.4
Almeida et al. (2014)	The most important processes in Italy	Heating, electricity and CO_2 enrichment	Heating, cooling and electricity as well as CO_2 enrichment
Torrellas et al. (2012b)	The most important in northern European countries	Heating and lighting	Heating and electricity
Khoshnevisan et al. (2014)	Climate change impacts of greenhouses in Iran	Heating and cooling	Heating and cooling

was the dominant process. Similar to climate change impacts, the two most significant parameters are node development rate and plant density which are related to crop growth. This means that for the same amount of material and energy consumption, higher node development rate and plant density contribute to more yield production and accordingly less environmental impact. However, node development rate is related to tomato cultivar and farmers cannot directly manage node development rate during cultivation. Therefore, they should pay attention to this parameter when selecting tomato cultivars for their greenhouse. However, cultivars with higher node development rate are more sensitive to greenhouse indoor conditions and are not an option for low-tech greenhouses, which cannot provide suitable indoor microclimates. Therefore, even though cultivars with higher node development rate produce more yield and less climate change impact, they only represent a realistic option for high-tech greenhouses. Similarly, higher plant density is favorable in terms of climate change impacts, but is only viable in greenhouses with appropriate heating and cooling distribution system to warrant sufficient crop respiration. After node development rate and plant density, cooling supply system for hot climates and heating supply systems for cold climates are the next most influential input parameters.

The analysis of future climate scenario on the greenhouse environmental performance reveals that it does not have the same impact everywhere. Moreover, parameter ranking order in future climate scenario shows that operation parameters affecting energy demands like day and night temperatures, CO_2 concentration and relative humidity will be more influential than design parameters like heating and cooling supply systems.

Adding economic analysis to the environmental impact methodology of the present work, would be helpful to provide reliable and comprehensive decision support. Furthermore, considering the influence of greenhouse dimensions could be another useful analysis to derive recommendations for greenhouse design. More crops analysis in addition to tomatoes and considering different types of heating and cooling distribution systems are the purpose of a near future paper by the authors. Furthermore, while in this paper we show which parameters are most influential in general, we also demonstrate that the specific ranking of these parameters depends on the site of the greenhouse. Hence, if greenhouse locations differ from the sites described here, the model needs to be parameterized to the specific location to draw conclusions on the main drivers of impacts.

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Appendix A. Supplementary data

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